

Gamma-rays from Collisions of Compact Objects with AGN Jets?

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Abstract. We consider different scenarios of collisions of compact objects (clouds, massive stars, supernova shock waves, or young pulsars) with jets in active galactic nuclei. The purpose is to find out if such collisions can become plausible explanations for the gamma-ray production in blazars. We conclude that the relativistic proton beam - cloud collision scenario has problems with explanation of the γ -ray spectrum in the observed energy range from blazars. As a result of collisions of massive stars, supernova shock waves, or young pulsars with the jet plasma, a highly oblique shocks should be formed. These shocks can accelerate electrons, protons to energies high enough for production of γ -ray photons observed in blazars. However, in order to produce observable γ -ray fluxes, the particles should be accelerated strongly anisotropically, which may be the case of highly oblique relativistic shocks in jets of AGNs.

1 Introduction

Gamma-ray production in blazars is usually interpreted in terms of a shock in the jet model. It is argued that relativistic shock moving along the jet accelerates electrons and/or protons, creating a blob of very energetic particles. These particles can then interact with the soft radiation produced in the blob itself by electrons, or with the radiation coming from the regions surrounding the jet (accretion disk, matter distributed around the jet). However some recent observations put some new light on the γ -ray blazars. It seems difficult to explain them in terms of this standard model. For example, VLBI multiple imaging of TeV BL Lac, Mrk 421, during 1994 - 1997 (30 images) show that 3 inner components moves only with subluminal speeds between projected linear distance 0.3 - 3pc [1]. The conclusion that the blobs do not move relativistically at such distances is the most likely interpretation of these observations. Moreover, another TeV γ -ray BL Lac, Mrk 501, show the base level X-ray and TeV γ -ray emission during its few months high activity period in 1997 [2]. Such emission is difficult to explain by a single shock in the jet scenario, but it would rather require continuous injection of shocks by the central engine into the jet.

Therefore we think that the investigation of other scenarios, in which production of γ -rays can occur efficiently, is justified. In one type of these non-standard models, γ -rays are produced in a cascade initiated by extremely relativistic particles accelerated

close to the disk surface (see e.g. [3, 4]), or by particles accelerated in almost rectilinear reconnection regions inside the jet (e.g. [5, 6, 7]). Other models predict production of γ -rays in collisions of hadronic beam with the clouds entering the jet[8] or as a result of interaction of relativistic jet with compact objects, i.e. massive stars[9], supernova front waves, or very young pulsars. In this paper we discuss these last type of models.

2 Collision of a cloud with the hadronic beam

It is possible that AGN jets contain relativistic hadronic beams propagating along the jet axis. Such beams of particles may be accelerated by the large scale electric fields generated by rotating accretion disks or black holes in a perpendicular magnetic field[10, 11], by a magnetic reconnection occurring on or close to the disk surface [12], by magnetic reconnection occurring inside the jet [13], or by highly oblique shocks present in the jet. It seems likely that the Broad Line Region clouds (BLR) enter frequently into the region of the jet. Such clouds, they are probably extended atmospheres of massive stars, have typical densities $\sim 10^{10} - 10^{12} \text{ cm}^{-2}$ and dimensions $\sim 10^{12} - 10^{13} \text{ cm}$. They can create significant target for relativistic hadronic beam. As a result, the distant observer located at the direction of the beam should detect variable γ -rays. The hadronic beam BLR cloud interaction model has been investigated even before the discovery of γ -ray emission from blazars (see e.g. Rose et al. [14]). It has been recently explored as a possible explanation of the blazar phenomenon by Dar & Laor [15] and Beall & Bednarek [8].

In our paper[8], we show that the energy losses of a hadronic beam on the excitation of plasma waves in the cloud dominate over pion production losses if hadrons have Lorentz factors below a few hundred. Therefore, the γ -ray spectra below $\sim 30 \text{ GeV}$ should be suppressed. This feature is in fact required by the observations of blazars which usually show lower fluxes at lower energy γ -rays and by the lack of strong variability at these lower energies (see e.g. the spectra of Mrk 421 and Mrk 501). However, the γ -ray fluxes expected in such a scenario below $\sim 300 \text{ MeV}$ are too low. It is difficult to find another mechanism which contributes significantly to this energy range. Thus, we conclude that hadronic beam - cloud interaction model has problems with explanation of the γ -ray spectrum observed from blazars at energies below $\sim 300 \text{ MeV}$.

3 Collision of a massive star with the jet

It is expected that active galactic nuclei are surrounded by huge stellar clusters containing $10^6 - 10^9$ stars. For example, observations of nearby relatively small galaxy, M32, show central stellar density of $\sim 2 \times 10^5 \text{ M}_{\odot} \text{ pc}^{-3}$ within $\sim 1 \text{ pc}$ [16]. Probability of stellar destruction as a result of star collisions depends on the escape velocity from the region containing the main mass of the star, on the radius of the star and on stellar density. The massive stars, with higher escape velocity, collide less frequently than e.g. Solar type stars. Simulations of the evolution of very massive stellar clusters with the black hole inside, show that significant amount of massive stars, instead of

colliding, finishes their life as a supernovae [17].

The massive stars, of the Wolf-Rayet (WR) and OB type, are characterized by very strong stellar winds. The high energy processes during interaction of such winds with the relativistic plasma of the jet has been recently investigated by Bednarek & Protheroe [9]. The pressure of the stellar wind can be estimated from

$$P_w = Mv_\infty/4\pi r^2 \approx 1.6 \times 10^4 M_{-5} v_3 / R_{12}^2 (r/R)^2 \text{ erg cm}^{-3}, \quad (1)$$

where the mass-loss rate of the star is $M = 10^{-5} M_{-5} M_\odot \text{ yr}^{-1}$, the wind velocity is $v_\infty = 3 \times 10^8 v_3 \text{ cm s}^{-1}$, $R = 10^{12} R_{12} \text{ cm}$ is the radius of the star, and r is the distance from the star surface. The wind pressure is balanced by the ram pressure of the jet plasma

$$P_j = L_j / \pi c \theta^2 l^2 \approx 15 L_{45} / \theta_5^2 l_{0.1}^2 \text{ erg cm}^{-3}, \quad (2)$$

where L_{45} is the jet power in units of $10^{45} \text{ erg s}^{-1}$, θ_5 is its opening angle in units of 5° , and $l_{0.1}$ is the distance in 0.1 parsec from the base of the jet. As a result of this interaction a double shock structure is formed at the distance from the star

$$r/R \approx 33 M_{-5}^{1/2} v_3^{1/2} \theta_5 l_{0.1} / R_{12} L_{45}^{1/2}. \quad (3)$$

It is shown [9], that such standing shock can accelerate electrons to high energies. These electrons can produce γ -ray photons by scattering thermal radiation coming from a massive star, and synchrotron X-ray photons in the magnetic field supplied by the star. However, observable γ -ray fluxes can be produced in such a model if the acceleration of electrons is highly anisotropic. Such situation might happen if electrons are drifting along the surface of the oblique shock (so called shock drift acceleration on the superluminal shocks). We estimated that many stars may be found inside the jet at the same moment which significantly increases the probability of detection of the γ -rays. The movement of the star through the jet and disturbances present in the jet and the stellar wind, which create instability in the location of the shock, can be responsible of strong variability of γ -ray emission from blazars.

4 Collision of a supernova shock with the jet

As we noted above, big number of massive stars in galactic nuclei should finish their life as a supernovae. The expanding supernova shell can significantly perturb the plasma flow in the jet if the pressure of material in the supernova front wave is comparable to the pressure of the plasma in the jet. The pressure of the supernova front wave can be estimated from

$$P_{\text{SN}} = L_{\text{SN}} / V_{\text{SN}} \approx 9 \times 10^{-3} L_{51} / r_{0.1}^3 \text{ erg cm}^{-3}, \quad (4)$$

where L_{51} is the supernova kinetic power, L_{SN} , in units of 10^{51} erg , and $r_{0.1}$ is the radius of the volume, V_{SN} , occupied by the expanding supernova in units of 0.1 pc. By comparing supernova shell pressure with the jet plasma pressure (Eq. 2), we can estimate the distance from the jet at which the expanding shell can perturb significantly the jet

$$r_{0.1} \approx 3.5 \times 10^{-2} (L_{51} \theta_5^2 l_{0.1}^2 / L_{45})^{1/3}. \quad (5)$$

It is clear that supernovae have to explode relatively close to the jet or have to find itself close to the jet at a later time after explosion as a result of initial fast motion of the presupernova star around the galactic nuclei. If the supernova is energetic enough, it may even completely obstruct the jet plasma flow for some time. It happens when the radius of the expanding supernova becomes comparable to the perpendicular extend of the jet defined by the jet opening angle and the distance from the base of the jet, i.e. $r_{0.1} = \theta_5 l_{0.1}$. This condition is fulfilled if

$$L_{51} \geq 1.5 \times 10^3 L_{45} \theta_5 l_{0.1}. \quad (6)$$

Therefore it may happen only for less powerful jets and at small distances from the base of the jet.

We suppose that the large scale shocks created by the supernova shock waves in the jet, may be much efficient accelerators of particles to very high energies than the classical supernova shock waves because of much stronger magnetic field strength in the shock region. The magnetic field strength in the jet, can be estimated if we assume that the magnetic energy density is in equipartition with the radiation energy density close to the base of the jet. From the observed UV power in the case of γ -ray blazar 3C 273 ($\sim 3 \times 10^{46}$ erg s $^{-1}$ [18]), we can determine the radiation energy density and so the magnetic field strength at the base of the jet. Assuming that the magnetic field in the jet drops inversely proportionally to the distance from the base of the jet l and that the shock created in the jet at the distance l extends far away along the jet, we estimate the maximum possible energies reached by particles with the charge Z on [19]

$$E_{Z,\max} \approx 10^{13} \chi Z / (1 + l/r_{\text{in}}) \text{ GeV}, \quad (7)$$

where χ is the acceleration coefficient (see next section for the expected value of χ), and $r_{\text{in}} \approx 9 \times 10^{14}$ cm is the inner radius of the disk in 3C 273 [18]. These energies can be comparable to the highest energies observed in the cosmic rays.

5 Collision of a very young pulsar with the jet

It is expected that in some explosions of massive stars also very young pulsars are formatted. The relativistic wind, produced by such very young pulsar, exerts a pressure

$$P_P = L_P / 4\pi r^2 c \approx 8.8 \times 10^{-4} B_{12}^2 / P_{\text{ms}}^4 r_{0.1}^2 \text{ erg cm}^{-3}, \quad (8)$$

where the rotational energy loss rate by the pulsar in the form of the wind is $L_P \cong 3 \times 10^{43} B_{12}^2 P_{\text{ms}}^{-4}$ erg s $^{-1}$, and B_{12} and P_{ms} are the surface magnetic field and the period of the neutron star in units of 10^{12} G and milliseconds, respectively. $r_{0.1}$ is the radius of the volume in which relativistic wind is confined in units of 0.1pc, and c is the velocity of light. If such a pulsar find itself inside the jet then as a result of the pulsar wind - jet plasma interaction a shock structure forms with the characteristic radius which can be estimated by comparison of Eqs. (2), and (8)

$$r_{0.1} \approx 7.7 \times 10^{-3} B_{12} \theta_5 l_{0.1} / P_{\text{ms}}^2 L_{45}^{1/2}. \quad (9)$$

We can also estimate the strength of the magnetic field in the shock region assuming that it is of a dipole type inside the pulsar magnetosphere and drops as r^{-1} with the distance r in the pulsar wind zone. It is equal to

$$B_{\text{sh}} \approx 0.14 B_{12} / P_{\text{ms}}^2 r_{0.1} \text{ G}. \quad (10)$$

Using Eq. (9) for the shock dimension, we obtain

$$B_{\text{sh}} \approx 18 L_{45}^{1/2} / \theta_5 l_{0.1} \text{ G}. \quad (11)$$

It is interesting that the value of the magnetic field in the shock region do not depend on the parameters of the pulsar but only on the parameters of the jet! The only condition which has to be fulfilled is that the jet pressure has to be balanced by the pulsar pressure in the pulsar wind zone. This happens for the condition

$$B_{12} / P_{\text{ms}}^3 > 2 \times 10^{-9} L_{45}^{1/2} / \theta_5 l_{0.1}. \quad (12)$$

The particles accelerated in the shock region, where the magnetic field strength is given by Eq. (11), gains energy at a rate

$$E = \chi Z e c B_{\text{sh}} \text{ erg s}^{-1}. \quad (13)$$

The maximum energies of electrons are limited by the synchrotron losses. In the absence of other losses, electrons can reach energies

$$E_{\text{max}} = 6 \times 10^4 (\chi / B_{\text{sh}})^{1/2} \text{ GeV}. \quad (14)$$

The maximum energies of synchrotron photons, produced by these electrons, are

$$\varepsilon_x \approx (B_{\text{sh}} / B_{\text{cr}}) (E_{\text{max}}^2 / m_e), \quad (15)$$

where $B_{\text{cr}} = 4.4 \times 10^{14} \text{ G}$. If the synchrotron photons with energies observed from the jet of Mrk 501, $\varepsilon_x = 2 \times 10^{-4} \text{ GeV}$, are produced by such electrons, then we can estimate the acceleration efficiency χ using Eqs. (14), and (15),

$$\chi \approx 2.8 \times 10^{-10} m_e B_{\text{cr}} \varepsilon_x, \quad (16)$$

which is $\chi \approx 10^{-3}$ for the above value of ε_x .

If the maximum energies of accelerated protons are limited only by their synchrotron losses, then protons can reach energies as high as

$$E_{\text{p,max}} = 2 \times 10^{11} (\chi / B_{\text{sh}})^{1/2} \text{ GeV}. \quad (17)$$

For the value of χ , estimated above, and the value of the magnetic field at the shock $\sim 10 \text{ G}$, obtained for typical parameters of the jet (Eq. 11), protons can reach energies as high as $\sim 2 \times 10^9 \text{ GeV}$. These protons still fulfill the condition that the dimension of the shock structure should be smaller than the Larmor radius of protons. However the maximum energies of protons can be limited by their energy losses in collisions with

synchrotron photons which are produced by accelerated electrons. The decay products of pions, created in proton-photon collisions (electrons, positrons and very high energy γ -rays), initiate cascade in the magnetic field. Such mechanism has been proposed as a possible explanation of blazar phenomenon (so called synchrotron-proton blazar model [20, 21, 22]). However the original version of this model requires magnetic field of the order of a few tens of Gauss in the blob moving relativistically along the jet in order to accelerate protons on sufficiently short time scale. Such magnetic fields seem to be unacceptable at larger distances from the accretion disk. However, as we show here, the magnetic fields of the required order should be present in the shock region if young pulsar collides with the relativistic jet. Although the shock considered by us is stationary in the jet frame, the relativistic flow of plasma through such highly oblique shock should result in strong collimation of accelerated electrons and protons, which is in fact equivalent to the situation that the shock moves relativistically through the jet. The radiation produced by electrons and protons will be strongly collimated along the shock surface, i.e. also along the jet axis.

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